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REPORT NO. 887.1D

CRYOGENIC LIQUID HEAT TRANSFER ANALYSIS

August 1987

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AEROSPACE STRUCTURES
INFORMATION AND ANALYSIS CENTER

OPERATED FOR THE FLIGHT DYNAMICS LABORATORY
BY ANAMET LABORATORIES, INC.

Report No. 187.1A

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FOREWORD

This report, prepared by Dr. Louis I. Boehman, Professor of Mechanical Engineering, University of Dayton, documents a study to use inert liquid cryogens to simulate liquid hydrogen-induced thermal effects. This work was performed with assistance from Dr. John J. Schauer, Professor of Mechanical Engineering and Department Chairman, and Mr. James Harold and Mr. Tom Stevenson, senior year Mechanical Engineering students at the University of Dayton. The work reported on herein was performed for the Aerospace Structures Information and Analysis Center (ASIAC), Wright-Patterson Air Force Base, Ohio. ASIAC is operated by Anamet Laboratories, Inc, under Contract F33615-84-C-3216. This effort was performed under Anamet Purchase Order No. 5961 in response to University of Dayton Research Institute Proposal No. R-6375.

The work was performed under in-house work unit 24010701 and was assigned Task Number 4.2-27. The task was requested by the Structural Integrity Branch, Structures and Dynamics Division, Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson AFB, Ohio. Mr. Michael Camden, Aerospace Engineer in the Loads and Criteria Group of the Structural Integrity Branch was the project monitor for this task.

The work reported herein was performed during the period 24 June 87 to 30 August 1987. This report was released by the author in December 1987 for publication.

Submitted by:

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ABSTRACT

The objective of the present study was to determine if there is a suitable cryogenic fluid which could serve to simulate the liquid hydrogen (LH_2)-induced loads and stresses during structural strength testing of large space transportation systems. Liquid helium (LHe) and liquid nitrogen (LN_2) were identified early on as the only pure cryogenic fluids which needed to be considered. Neon, while being a promising candidate based on its cryogenic properties, simply is not available in large enough quantities to warrant consideration. The study showed that the primary factor to be considered in choosing a simulant was the magnitude of the heat leakage rate that could be expected to apply to the structure. Analysis of several generic hydrogen fuel tank designs showed that heat leaks in the range of 100 to 500 Btu/hr-ft^2 could be expected. Expressed in alternate terms, this would roughly correspond to LH_2 boil-off rates of 10 to 30 percent per day.

Based primarily on heat transfer considerations it was concluded that LHe essentially duplicates LH_2 thermal effects providing the tank pressure of the test vehicle is less that 26.6 psia(0.183 mPa). It was also found that liquid nitrogen duplicates LH_2 effects providing the 57 ^oK difference in boiling temperatures of these two cryogens is accounted for.

It was also determined that real difficulties can be expected in simulating LH_2 effects in the ullage space of a fuel tank. Based on heat transfer considerations, it is shown that helium as a simulant will over-cool the tank walls around the ullage space and the opposite is true for nitrogen.

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I. INTRODUCTION

Studies on advanced aerospace vehicles employing liquid hydrogen (LH_2) as a fuel--those conducted during the 1960's as well as during the 1980's--have clearly pointed out the tankage system as a major problem area. A number of tankage concepts applicable to all classes of hydrogen fueled, hypersonic cruise vehicles have been developed ranging from purely non-integral to fully integrated structures. Successful design and fabrication of large, lightweight, leak-tight tanks based on present day concepts has proven to be an elusive undertaking, even for non-integral tanks. Eventually however such tanks will be successfully built and then they must be tested.

AFWAL/FIBE is currently involved in a combined in-house and contractual study with the objective of developing methods to safely test this on-coming generation of aerospace vehicle fuel tanks. The emphasis of this study is to determine if an inert cryogen can be found which will duplicate or at least come acceptably close to duplicating the thermal effects of LH_2. The first effort of this program was done at Ohio State University by Dr. L. S. Han. He conducted a preliminary investigation on the feasibility of using liquid helium (LHe) as a LH_2 simulant and concluded that with modified testing techniques and appropriate analytical methods, an inert cryogen such as LHe could be used to simulate the thermal effects of LH_2[1]. Han's study considered only film boiling as the likely heat transfer regime to be encountered, whereas when the entire mission is considered, from ground-hold to re-entry, other, less severe, heat transfer regimes will also be encountered. Since the greatest loads on such vehicles will be encountered on or shortly after takeoff and not on re-entry, it was clear that a rational analysis of the simulant problem would require an in-depth analysis covering all modes of cryogenic heat transfer. Thus one of the objectives of the present study was to establish the state-of-the-art in cryogenic heat transfer, specifically free convection pool boiling, nucleate boiling, and film boiling.

In 1964, the Air Force Flight Dynamics Laboratory contracted the Convair division of General Dynamics to design, fabricate,

and functionally demonstrate a large volume, lightweight, non-integral LH_2 tankage system applicable to a Mach 6 manned hypersonic cruise vehicle[2]. One of the objectives of that effort was, incidentally, to determine if LN_2 could be used as a simulant for LH_2. Based on the results of that undertaking, it was abundantly clear that the rational approach to accomplishing the objectives of the present study would entail the following tasks:

(1) Establish the range of heat fluxes that will be encountered by the external walls of the LH_2 fuel tanks or, equivalently determine representative LH_2 boil-off rates that fuel tank designers are considering.

(2) Determine the boiling heat transfer characteristics of LH_2, LHe, and LN_2, the free convection, and forced convection heat transfer characteristics of both subcooled and gaseous states of H_2, He, and N_2. In particular, determine the best heat transfer correlation formulas that can be used to analytically compute heat fluxes from these three cryogens to fuel tank walls.

(3) Since heat transfer correlation formulas necessarily require knowledge of a wide range of thermodynamic and transport properties, determine sources of the best such data for these cryogens.

(4) Perform the necessary analyses to determine if the thermal effects of LH_2 can be duplicated by the two inert cryogens-LHe and LN_2.

(5) Perform thermal stress computations for representative LH_2 tankage structures using representative heat fluxes and heat transfer coefficients for the three cryogens as determined from Task 2, the intention being to use an AFFDL/FIBE in-house computer program called THASIS to perform one-dimensional thermal stress analyses.

(6) Investigate the prospects for determining the three-dimensional temperature field in the walls of LH_2 fuel tanks, taking into account the typical use of variable thicknesses of insulation on various sections of the tank and the temperature stratification that occurs inside cryogenic fuel tanks.

In the following sections, the work done in accomplishing each of these six tasks is described along with the results which have been obtained to date.

II. REPRESENTATIVE LH_2 HEAT FLUXES.

Volumes I and III of Reference 2 both provide heat flux data that can be used to estimate representative values. In that work a 6000 gallon LH_2 tank was designed, built, and extensively tested. The tank had a "Siamese" configuration; consisting of a main shell, 20 feet in length, with a cross-section of two intersecting circles, 64 inches in diameter and an 8-foot total width, enclosed by ellipsoidal dome bulkheads. The insulation used on the tank was micro-quartz in a helium atmosphere. In Volume I a heat flux of 63 Btu/hr-ft^2 (0.0199 W/cm^2) was estimated for ground hold conditions and a maximum of 135 Btu/hr-ft^2 (0.043 W/cm^2) under flight conditions for an insulation thickness of four inches. In Volume III ranges of heat fluxes from 25 to 475 Btu/hr-ft^2 were estimated for ground hold to maximum conditions.

For the purposes of the present study, a worst case heat flux of 500 Btu/hr-ft^2 (0.16 W/cm^2) was assumed. The important implication of a heat flux of this magnitude is that, as will be shown in the next section, the nature of the boiling occurring in LH_2 will be in the free convection pool boiling to nucleate boiling regimes and definitely not in the film boiling regime.

III. HEAT TRANSFER CHARACTERISTICS OF LH_2, LHe, AND LN_2

A review of the extensive data base generated during the 1960's on the boiling heat transfer of these three cryogens revealed the following information: The popular Rohsenow nucleate pool boiling correlation[3] was not adequate for predicting the boiling heat transfer characteristics of these three cryogens whereas the Kutateladze nucleate pool boiling correlation[3] was surprisingly accurate. It was also found that the Kutateladze correlation for the maximum nucleate boiling heat flux[3] was the preferred formula for these three cryogens. For free convection pool boiling, the classical McAdams correlation[3] was found to be very adequate.

Figure 1 shows free convection pool boiling predictions for the three cryogens of interest according to the McAdams correlation. In Figure 1, delta T ($T_{wall} - T_{sat}$) is plotted as a function of heat flux. Observe the characteristically small delta T's associated with free convection pool boiling. Figure 2 shows the nucleate boiling curves for LH_2 obtained with both the Rohsenow and the Kutateladze correlations. Figure 3 shows the same two correlations evaluated for LN_2 while Figure 4 was done for LHe. One observes that the Rohsenow correlation is only satisfactory for LH_2. An extensive amount of experimental data exists for these three cryogens[4,5] and all of these data are well correlated by the McAdams formula for the free convection range, by the Kutateladze formula for the nucleate boiling range, and by the Kutateladze formula for maximum (burnout) heat flux.

Figure 5 shows a characteristic boiling curve covering the complete spectrum of boiling regimes for a cryogenic liquid. Figure 6 shows the actual boiling curves for the three cryogens of interest for a tank pressure of one atmosphere. Also shown on Figure 6 are the representative heat fluxes for maximum and minimum conditions. All the information presented so far clearly shows that free convection and nucleate boiling are the important heat transfer regimes to be considered in LH_2 simulant studies.

This is not to say that film boiling will never occur in LH_2 fuel tanks. Obviously violent film boiling will occur during chill-down of tanks being placed into service for the first time

or after they have been run dry. Reference to Figure 6 will show that anytime the tank wall temperature exceeds T_{sat} by more than 10 ^{o}K, film boiling will occur.

One might be inclined to think that, because of the hysteresis effect associated with the minimum heat flux, it may be impossible to reach a stable free convection or nucleate boiling condition following chill-down of a LH_2 tank. The results given in Figure 6 show that heat fluxes in the range of ground hold conditions are considerably less than the minimum heat for all three of the cryogens considered in this study , even-for-LHe. Thus, with the amount of thermal insulation that is being currently envisioned for LH_2 fuel tanks, it should be be no problem to actually reach a stable free convection boiling situation when using either LHe or LN_2 as a LH_2 simulant.

IV. THERMODYNAMIC AND TRANSPORT PROPERTIES OF CRYOGENS

During the late 1950's and early 1960's the Flight Dynamics Laboratory was a major sponsor of research directed toward the determination of thermodynamic and transport properties for a wide range of aerospace materials, including cryogenic fluids[6]. During the 1970's the National Bureau of Standards and NASA developed tables of thermodynamic and transport properties for a wide range of cryogenic fluids including He, H_2, and N_2. The NASA compendium of H_2 properties[7] is state-of-the-art and was used to compute the correlation curves shown in Figure 2. The NBS table of properties for He[8] was the source of thermodynamic and transport properties used to compute the correlation curves shown in Figure 4 and the NBS table of properties for LN_2[9] was used to prepare Figure 3. These three sources of thermodynamic and transport property data were adequate for accomplishing the immediate goals of the current effort. The use of tables of course is unwieldy for large scale computation efforts and for detailed design studies of tankage systems. Therefore a search was conducted for computer codes that could be used to analytically predict thermodynamic and transport properties for these three cryogens. A number of such codes were located including one that was specifically set up for microcomputers[10]. Unfortunately this latter code did not include computation of the properties for liquid H_2 and so was not deemed useful for AFFDL/FIBE purposes. The most comprehensive and well documented code that was found and eventually made to work on the FDL VAX computer was the NASA code called GASP (GAS Properties)[11]. This code was found to be quite easily adaptable to 16 bit microcomputers operating with the LAHEY or MICROSOFT (Ver. 4) FORTRAN77 compilers.

GASP predicts thermodynamic and transport properties that agree very well with the data given in References 7, 8 and 9. In addition the code provides the often hard-to-locate properties that are essential to boiling heat transfer computations such as surface tension, isothermal compressibility, and coefficient of volume expansion.

V. LIQUID HYDROGEN FUEL SIMULANT ANALYSES

Based on the considerations of the previous Sections it was determined that the boiling of any of these three cryogens would be in the free convection boiling range during ground hold conditions and predominantly in the nucleate boiling range during most flight conditions. Because of the high heat transfer coefficients associated with nucleate boiling and the extremely small delta T's associated with free convection, for all three cryogens, the effect of temperature gradients between the inner wall of the fuel tank and the liquid cryogen will be extremely small. Thus thermal stresses induced by temperature gradients at the liquid cryogen-fuel tank inner wall will not be influenced to any appreciable degree by substituting LHe for LH_2 during the structural testing process. Recall that in nucleate boiling, the temperature difference between liquid and the surface on which the boiling occurs is in the range of tenths to several degrees so that thermal stresses are not generally a problem for surfaces on which nucleate boiling occurs.

LN_2 can under some conditions be used as an LH_2 simulant. Boiling of LN2 is not the primary concern, but rather the 57 ^{o}K difference in normal boiling temperatures (77 ^{o}K for LN_2 versus 20 ^{o}K for LH_2) and the effect it has on the average thermal conductivity of the thermal insulation system over the temperature range imposed on the total thickness of the insulation. Super insulations do have a greater slope of thermal conductivity (k) versus temperature (T) at cryogenic temperature than do most other candidate thermal insulations. However the effect that the 57 ^{o}K temperature difference has on the <u>average</u> thermal conductivity over a temperature difference of boiling temperature to say standard room temperature (298 ^{o}K) for typical super insulations is quite small. Modern aerospace composite metal structures such as Rene'41 honeycomb panels also have this same characteristic[12,13]. So while every fuel tank design has to be evaluated on an ad hoc basis, it appears that as far as heat transfer and thermal stresses are concerned, the 57 ^{o}K temperature difference between LN_2 and LH_2 normal boiling temperatures is not a major concern. It should be noted that in Volume III of

Reference 2 it was concluded that heat fluxes differed by only 5 percent when LN_2 was used as a substitute for LH_2.

Obviously, the much greater density of LN_2 over that of LH_2 (11.5:1) seriously affects the total structural loads on the tankage system. A solution to this problem is to use an internal helium gas filled bladder within the tank to occupy most of the internal tank volume. Designing an anchorage system to keep the bladder in place under the action of the buoyancy force acting on the bladder in such a manner that the anchorage system does not significantly affect the structural loading on the tank would need to be considered.

Fuel tank pressure must also be taken into account when considering LHe as a simulant because the critical point pressure of LHe (.228 mPa) is very low compared to LH_2 (1.293 mPa) and LN_2 (3.384 mPa). Because of large pressure fluctuations which can develop during boiling heat transfer in the near-critical point region, the possibility exists that unusually large unsteady loading can develop within a fuel tank if LHe is substituted for LH_2 and if the tank pressure is allowed to rise to near-critical point conditions[14]. According to a number of investigators, if the pressure is limited to 80 percent of the critical point pressure, then no large-scale pressure fluctuations should be encountered during nucleate boiling. Therefore LHe cannot be considered to be a simulant for LH_2 if the tank is designed to operate at pressures in excess of .184 mPa(26.6 psia).

Pressure rise considerations also place an additional requirement on structural testing with LHe. Because the latent heat of vaporization per unit volume of LHe is only one tenth that of LH_2, a given heat flux will cause a significantly greater gas generation rate for helium compared to hydrogen. Therefore, the size of the venting system on the tank must be proportionately increased when testing with LHe.

The above observations about the suitability of LHe and LN_2 as LH_2 simulants cannot be as optimistic when a significant percentage of the tank volume is ullage space. Because gas heat transfer coefficients are at least an order of magnitude smaller than their liquid counterparts, the inner skin temperature will

be significantly different from the adjacent ullage space vapor. Therefore one cannot adjust the outer skin temperature by a simple factor to maintain the same temperature gradient in the tank wall that is exposed to vapor.

One also has to consider the relative boil-off rates of the liquid cryogens and how these gas generation rates will affect the cooling of the ullage space tank walls. First, consider LHe. For a given surface heat flux, the gas generation rate of LHe will be about 20 times greater than that of LH_2 on a mass basis (10 times higher on a volumetric basis). But the specific heat of gaseous He (GHe) at its normal boiling point temperature is just about the same as that of gaseous H_2 (GH_2) at its normal boiling point. Therefore the excessive GHe generation will cause the ullage space inner skin to run much cooler than would be obtained with LH_2. The opposite situation exists with LN_2. The gas generation rate of gaseous N_2 (GN_2) will be less than half that of GH_2 while the specific heat of GN_2 is only 11 percent that of GH_2. Thus the inner skin of the portion of the tank wall exposed to GN_2 will run much hotter than when LH_2 is used as the cryogen.

In order to use LN_2 as a simulant for LH_2 when testing partially full tanks, additional cooling of the gaseous nitrogen must be provided in order to maintain ullage space thermal similarity. With LHe as the simulant, a means must be found to add heat to the gaseous helium so that the unavoidable excessive helium vapor generation rate does not over cool the tank walls exposed to vapor.

VI. WORK DONE WITH THASIS COMPUTER PROGRAM

The in-house computer program THASIS (Transient Heating and Stresses in Slabs) was available for performing thermal stress analyses of LH_2 tank structures when filled with various cryogens. While this program is a 1-D code and therefore limited in scope, it was thought that because of its simplicity it could serve as a screening tool for determining the major effects on thermal stresses cause by using a simulant rather than LH_2.

The documentation available for this code was non-existent. Therefore it was decided to write a USER's manual for it. This was accomplished. Some problems were set up for analyzing LH_2 tank structures. This exercise involved obtaining thermal conductivities for the various components of typical tank walls, which are composite structures involving multilayered insulation systems and honeycomb panels. The program was run for a number of problems at which time it was decided that the program could be improved significantly, primarily from a user's point of view, if it were made interactive. A major rewrite of the program was undertaken and completed along with the appropriate revisions made to the USER'S manual.

At the present time, THASIS is a much-improved, much easier program to use.

VII. A THREE-DIMENSIONAL TEMPERATURE FIELD COMPUTER PROGRAM

As a side effort to the main thrust of this investigation, it was proposed that eventually a computer program would be needed to analyze the complete temperature field in both the walls of a cryogenic fuel tank as well as in the cryogenic fluid itself. Since the author of this report had ten years of experience in writing and working with three dimensional fluid flow computer programs based on panel methods, it was thought worthwhile to investigate the possibility of converting an existing 3-D fluid dynamic computer program to a program which could also be used to solve thermal problems. The rationale behind this undertaking was that in both cases, the same partial differential equation, Laplace's Equation, is involved.

In the panel methods--those based on surface singularities--the velocity potential is never determined. Only the velocity field itself is usually of interest. The counterpart to the velocity potential in a thermal problem is of course the temperature while the counterpart to the velocity is the heat flux. Thus the main task in converting a panel method program was to add the equations for the velocity potential to such a program.

Under the present contract, the equations for the velocity potential were determined and were added to the author's panel method program. What remains to be done is to set up and implement a scheme for adding the extra input data to the program which is required to solve heat transfer problems. This final task involves specifying the boundary conditions which are applicable to each panel.

VIII. CONCLUSIONS

This study has shown that both LHe and LN_2 can be used to simulate the thermal effects of LH_2 in aerospace structures. The degree of thermal similarity obtained depends on the level of the liquid in the tank. The highest level of similarity is obtained when the tank is full of liquid. The thermal similarity obtainable with either LHe or LN_2 gets progressively worse as the liquid level decreases.

At the present time it is evident that the use of LN_2 shows the greatest promise as a simulant for LH_2 from both technical and cost considerations.

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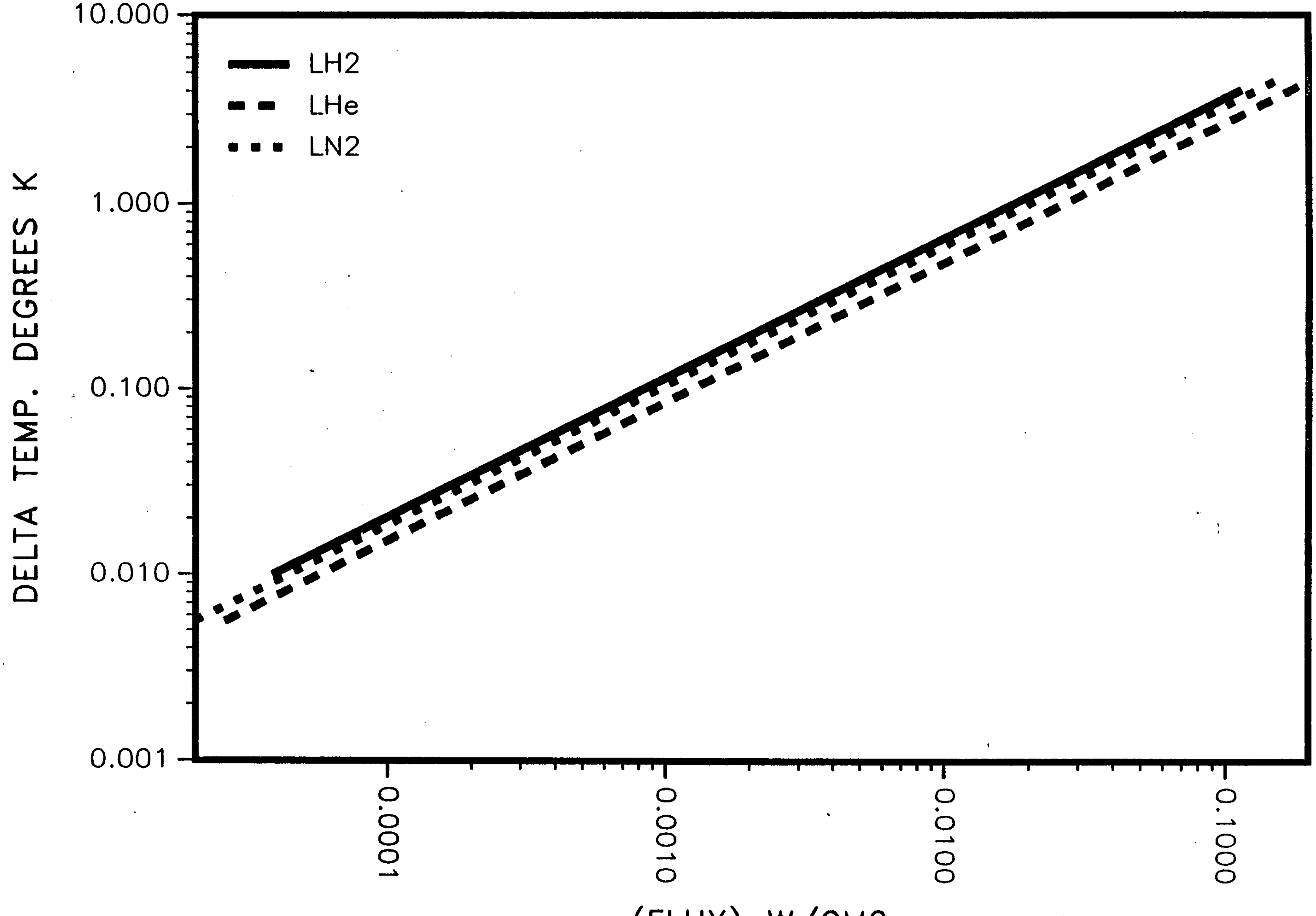

Figure 1. LH2, LHe and LN2 Convection Heat Transfer Rates

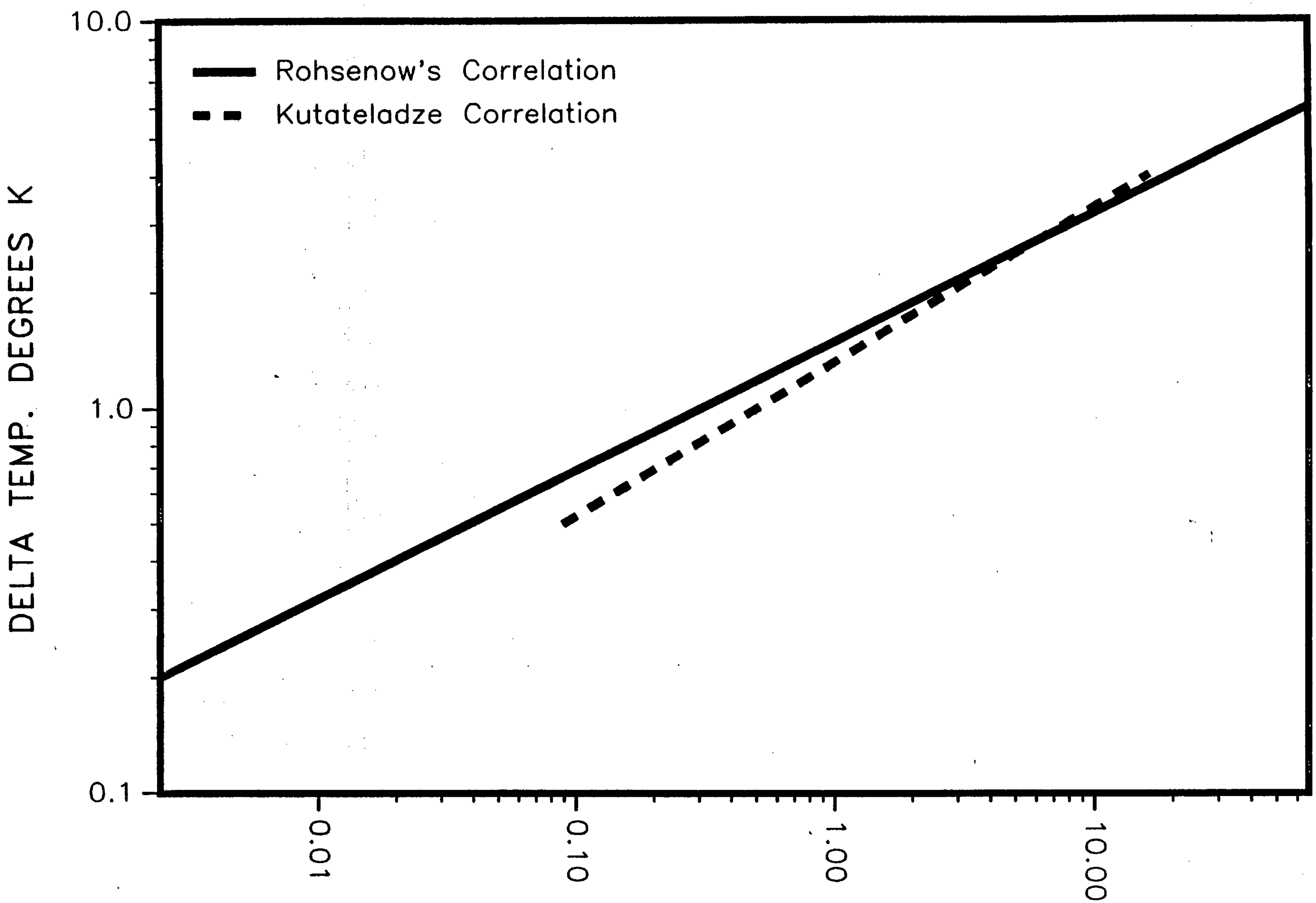

Figure 2. LH2 Boiling Heat Transfer Rates

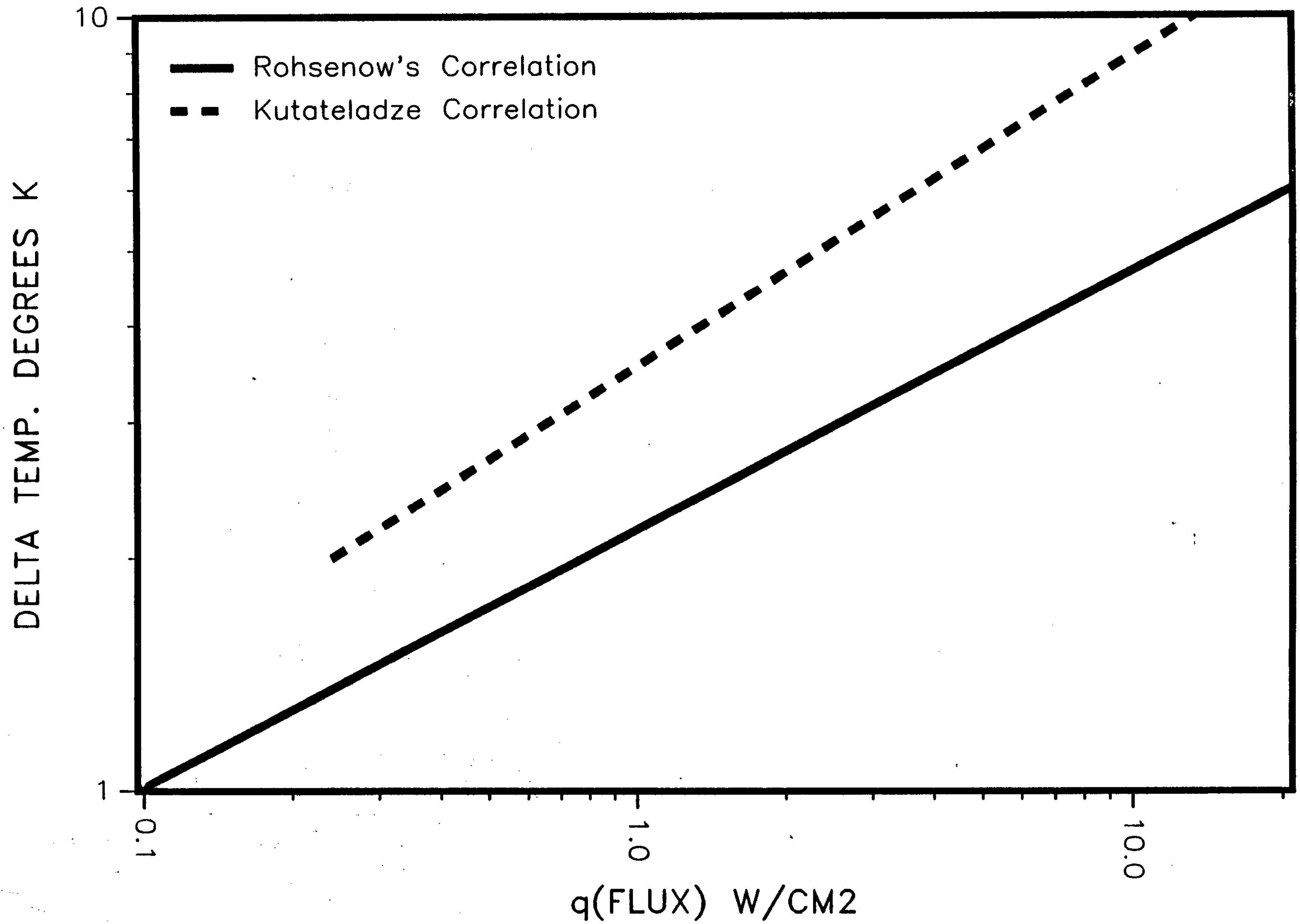

Figure 3. LN2 Boiling Heat Transfer Rates

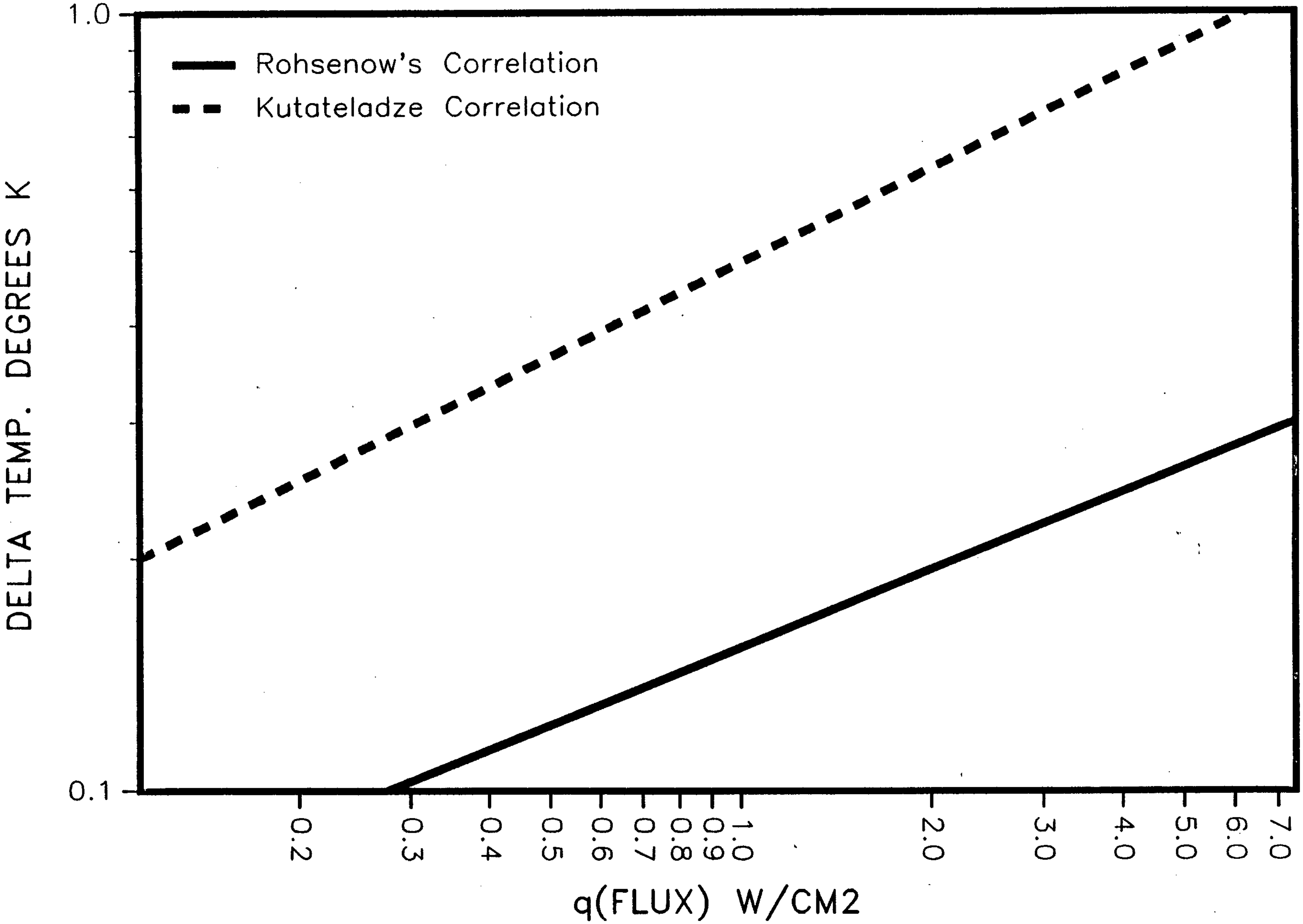

Figure 4. LHe Boiling Heat Transfer Rates

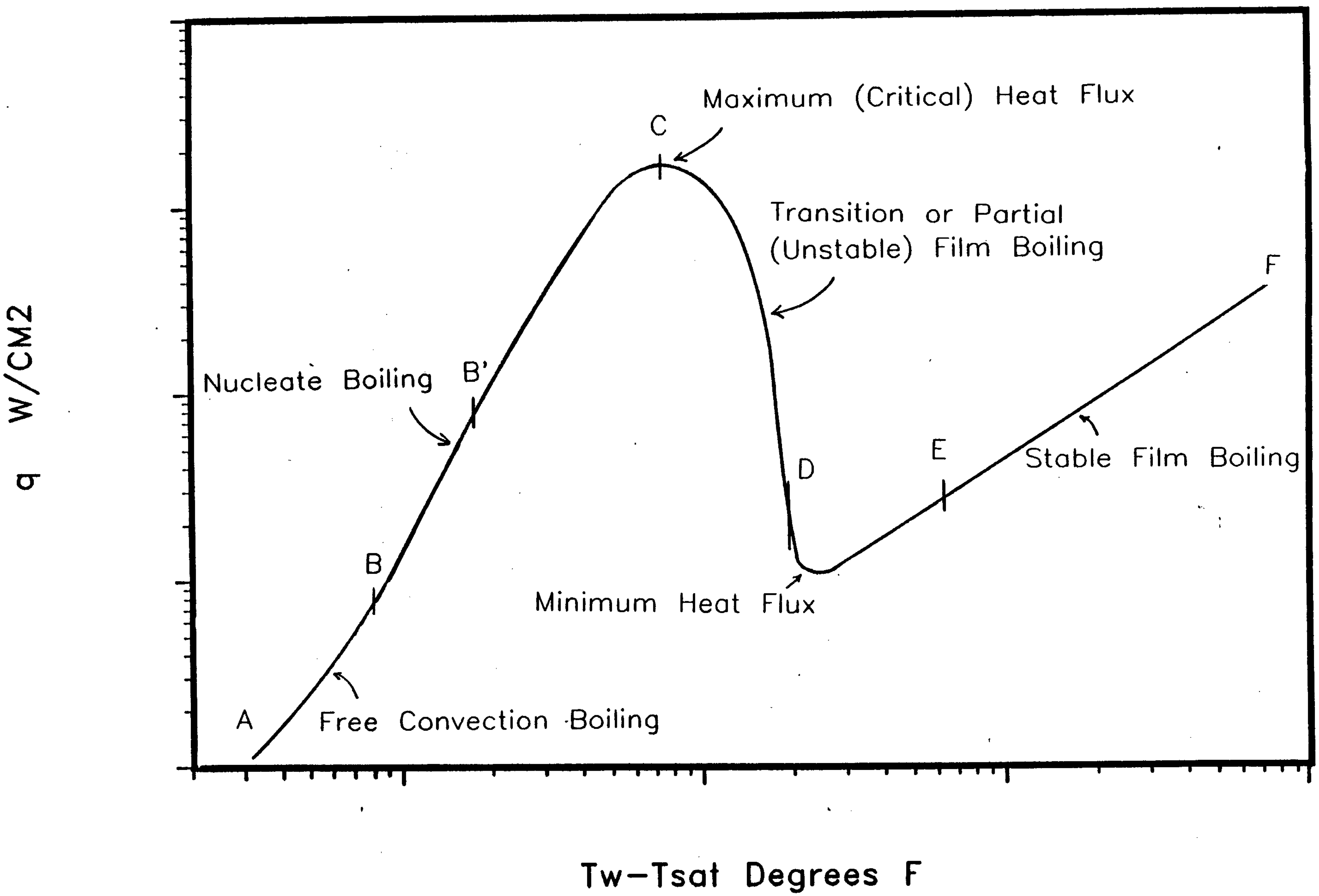

Figure 5. Characteristic Boiling Curve For Cryogenic Liquids

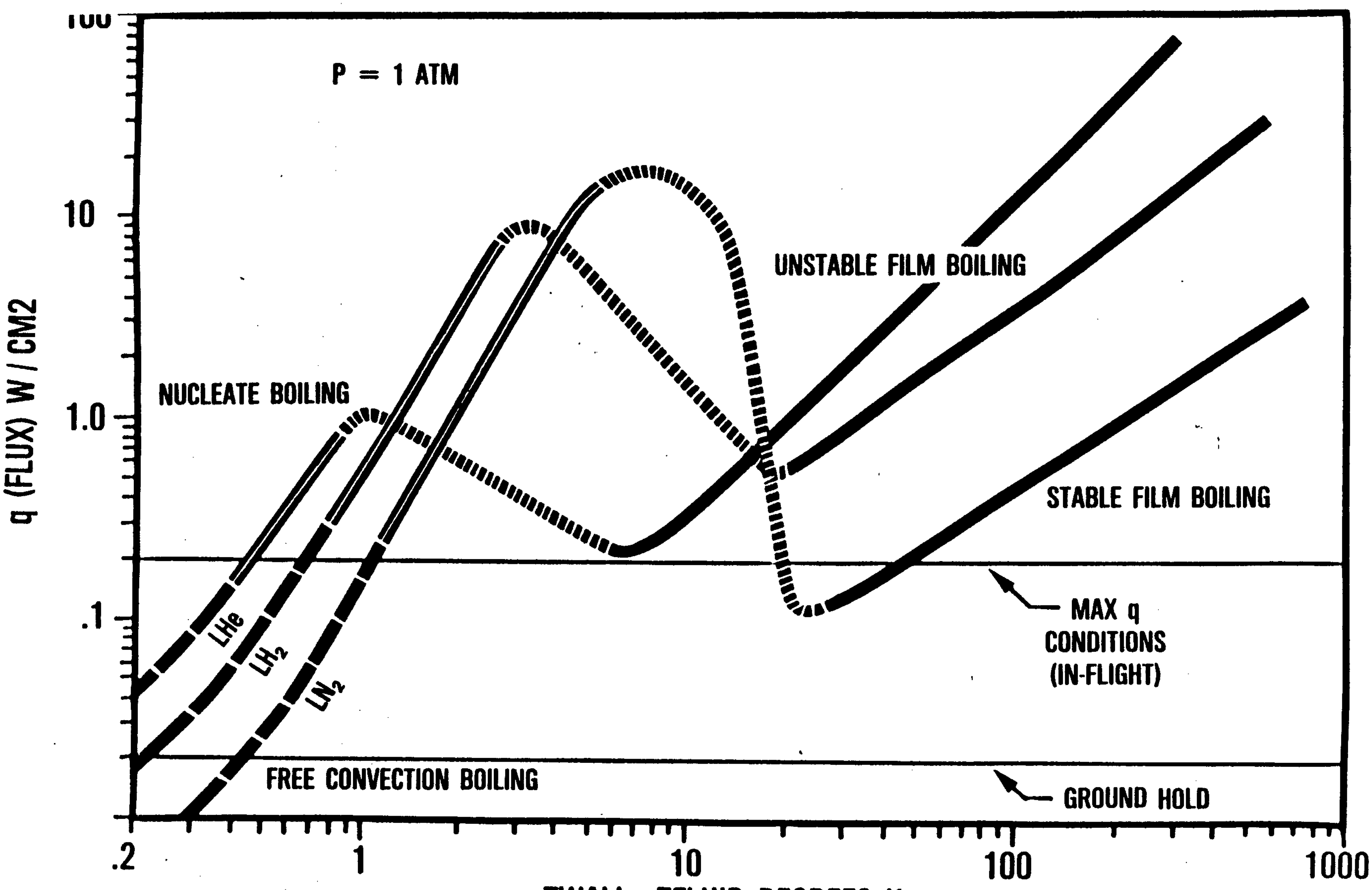

Figure 6. CHARACTERISTIC BOILING CURVE FOR CRYOGENIC LIQUIDS